Strategic Design Tool for Reverse Engineering in Permanent Magnet Synchronous Motor Applications

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ABSTRACT

The development of electrical machines consists of different design steps, the analytical calculations, numerical computations, thermal analysis and dynamic simulations. The design of permanent magnet machines is more efficient if these tools are implemented in one overall software tool, starting from a minimum of data and trying to find an optimum motor subject to a number of constraints. Here, a calculation scheme is presented that accounts for the mechanical parameters, magnetic characteristics, the supply system via an equivalent circuit model and the thermal behaviour as well. Two different examples are used to demonstrate the flexibility of the developed design tool. The first one deals with a high performance drive, requiring flux weakening for high speed: a drive motor for hybrid vehicles. The second one aims at high efficiency: a pump application using a photovoltaic energy source.

1. INTRODUCTION

Permanent magnet motors are increasingly widespread in very different applications. In many systems the high dynamic performance of the permanent magnet motor is recommended [1-3]. Examples are machine tools servodrives and drives for electric or hybrid operated vehicles. When compared to a brushed dc-motor, the brushless motor requires less maintenance and the dynamic response is not limited by the mechanical commutation. For high speed applications, where flux weakening is required, the permanent magnet motor offers possibilities and is a valuable competitor of the induction motor [4]. An other feature of the permanent magnet synchronous machines (PMSM) is its high efficiency [5]. This is beneficial when the electrical energy source consists of a battery or photovoltaic system.

Because the drive requirements are very different, many design and analysis tools and strategies are developed which are specifically aiming at a particular application. The characteristics of a machine are often calculated using the finite element method and the results are a fine tuning of the geometrical shape of the machine [7,8]. With the different requirements on the one hand and the limited scopes of the existing tools on the other hand, a general software tool is developed which starts from a minimum of data and tries to find an optimum motor subject to a number of constraints. The final aim is to have a calculation scheme, that accounts for the magnetic characteristics, the supply system via an equivalent circuit model, mechanical parameters and the thermal behaviour. The calculation time has to be minimised in order to enable the evaluation of various construction variants in an optimisation process. A trade-off between calculation time and accuracy has to be found.

2. ELEMENTS OF THE DESIGN TOOL

The design process consists of different design steps and therefore the overall design tool is organised in the same way. The analytical calculation of the motor behaviour and the numerical computations to extract electromagnetic and thermal parameters for lumped parameter models to be used in a dynamic system simulation.

2.1 Analytical Calculations

In a first step the motor is designed by analytical calculations based on the generalised electric machine theory [9]. A PMSM can be modelled by mathematical equations assuming that subject ferromagnetic materials have an infinite permeability and that slot effects can be adequately considered by a Carter factor. The analytical calculation, forming the key portion of the design tool, contains a lot of empirical formulae. This step has the advantage to be able to study different design considerations in a rather short time. Input data are the required motor properties (supply voltage, mechanical power, torque and speed). A number of constraints are given, such as maximum outer diameter, moment of inertia, current density, to mention a few. All material parameters have to be supplied as well. For permanent magnet material the demagnetisation characteristic, the electrical resistivity and its temperature dependency are important. The non-linear ferromagnetic characteristics and loss parameters are provided for the iron parts in the machine. For the conductors the conductivity and the maximum operation temperature of the insulation material (insulation class) are representing the input data. The calculation procedure is started and the motor characteristics are evaluated and compared with the given requirements and constraints. New dimensions are found and the iteration process is restarted until the desired motor parameters are obtained. The flow chart of this first design step is given in Figure 1.

2.2 Numerical Computations

The analytical calculations contain a lot of empirical formulae which have to be verified by a numerical field analysis in a second step. When a motor model is found by the analytical iteration, the necessary data are created to start a finite element computation. The data are stored in ASCII form files to automate the visualisation of the motor model, the mesh generation, the problem definition as well as the computed results by the post-processor (Figure 2). Several finite element solutions are required in order to find all parameters that have to be checked. To evaluate the steady state torque under linear considerations, as found from the analytical solution, only one FEM solution is required. If the torque ripple has to be evaluated, the numeried solution process must be repeated for multiple rotor positions. By supplying the transient short circuit current to the model the permanent magnet material is checked if irreversible demagnetisation occurs. Important for a dynamic control strategy is the dependency of the inductances due to saturation effects. In two solutions the d- and q-axis inductances are found [9].

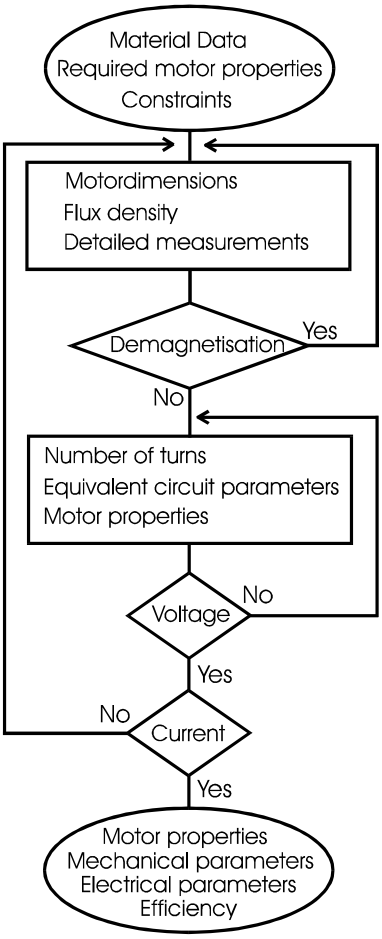

Figure 1: Analytical calculation (flow chart).

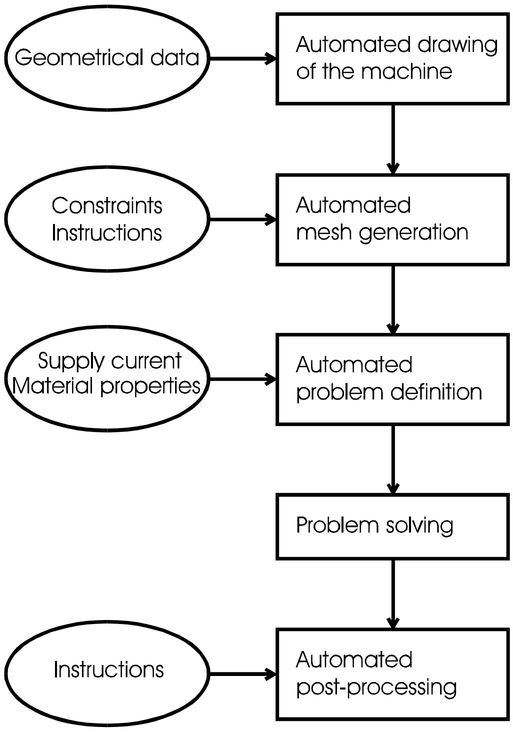

Figure 2: Automated FEM computation.

2.3 Thermal Analysis

High performance of electric drives is obtained by allowing the machine to operate above its rated load for a short period of time. The overload capability is restricted by the maximum temperature. The thermal computation is performed in order to evaluate the thermal stability of the permanent magnets and to check whether the insulation class of the copper windings is sufficient. The temperature as function of the time is determined by numerical integration of the differential equations of the thermal equivalent circuit (TEC). The elements of the TEC, the thermal capacity and conductivity, are obtained by an analytical approach, while losses are computed using the FEM. Using the TEC the temperature of the armature winding can be derived as a function of the load cycle to be implemented in the dynamic simulation algorithm.

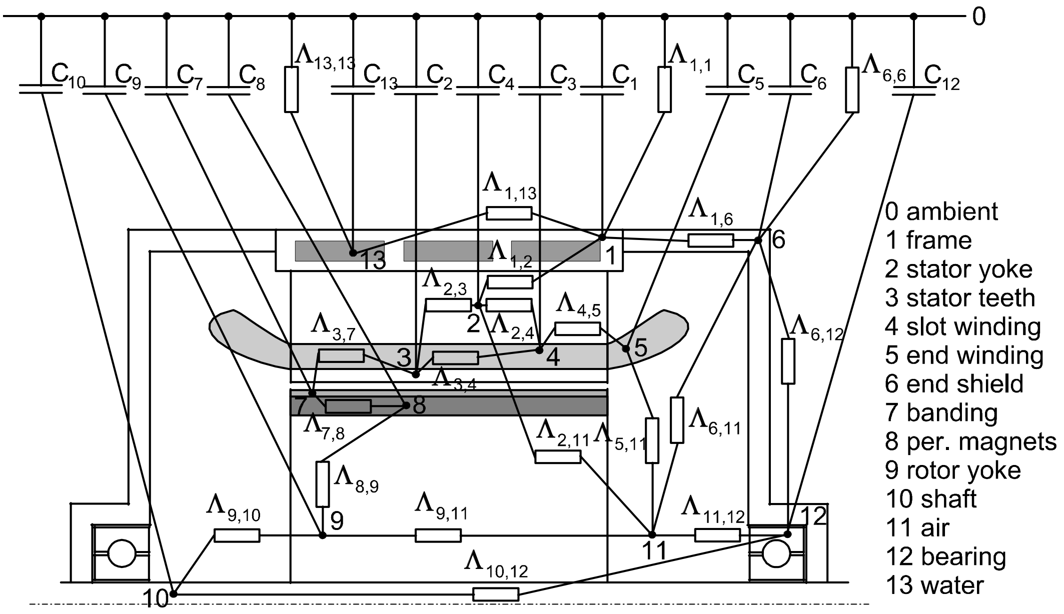

Figure 3: TEC of a water-cooled PMSM [11].

2.4 Dynamic Simulation

At this instant of the design, all data are prepared to start the final step of the design process. Using numerical simulation techniques (SIMULINK®), the dynamic behaviour is verified. However, the control algorithm is varying with the machine application. For each motor type the system has to be modified, e.g. field weakening has to be implemented or the influence of a damper cage used in open loop applications is studied. The control algorithm is operated by the equivalent circuit model of the machine. The mechanical parameters from the analytical calculation are supported by the electrical parameters from the FEM as function of saturation effects and the temperature depending parameters from the TEC computation as function of the load cycle. If all system requirements are met, the design procedure is terminated.

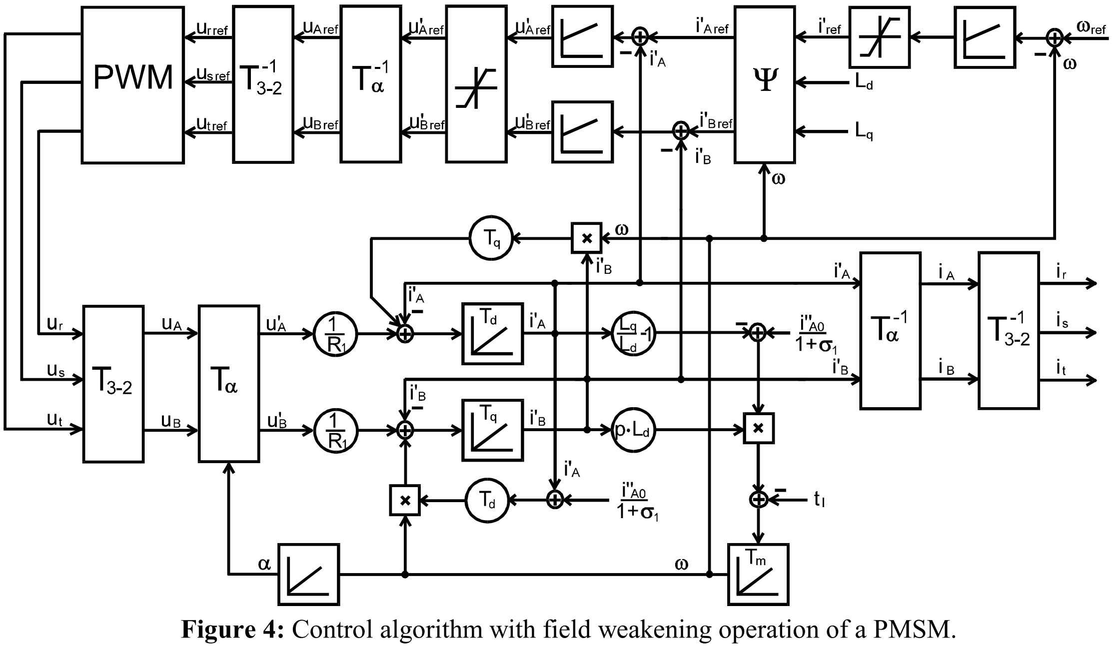

Figure 4: Control algorithm with field weakening operation of a PMSM.

2.5 Design tool

The connection of different design methods into one overall development tool is aiming on the study of design modifications or variants of the electrical power supply. The effect of e.g. modifications of the air gap width, variations of the permanent magnet material characteristics or alternations of the quantity of cooling-water can be promptly examined by evaluating the dynamic and the thermal behaviour of the drive system. The four levels of this design methodology are illustrated in Figure 5. The overall design system is automated in such a way, that the output of each step serves as an input for the next step. The numerical magnet field calculation may be supplemented by a thermal field computation, in order to get the local temperature distribution in each part of the machine. Using this approach, the computed data can be used directly as input for the manufacturing process: By using spark erosion to produce the stack laminations the machine programmation is taking advantage of the output data of the optimisation procedure.

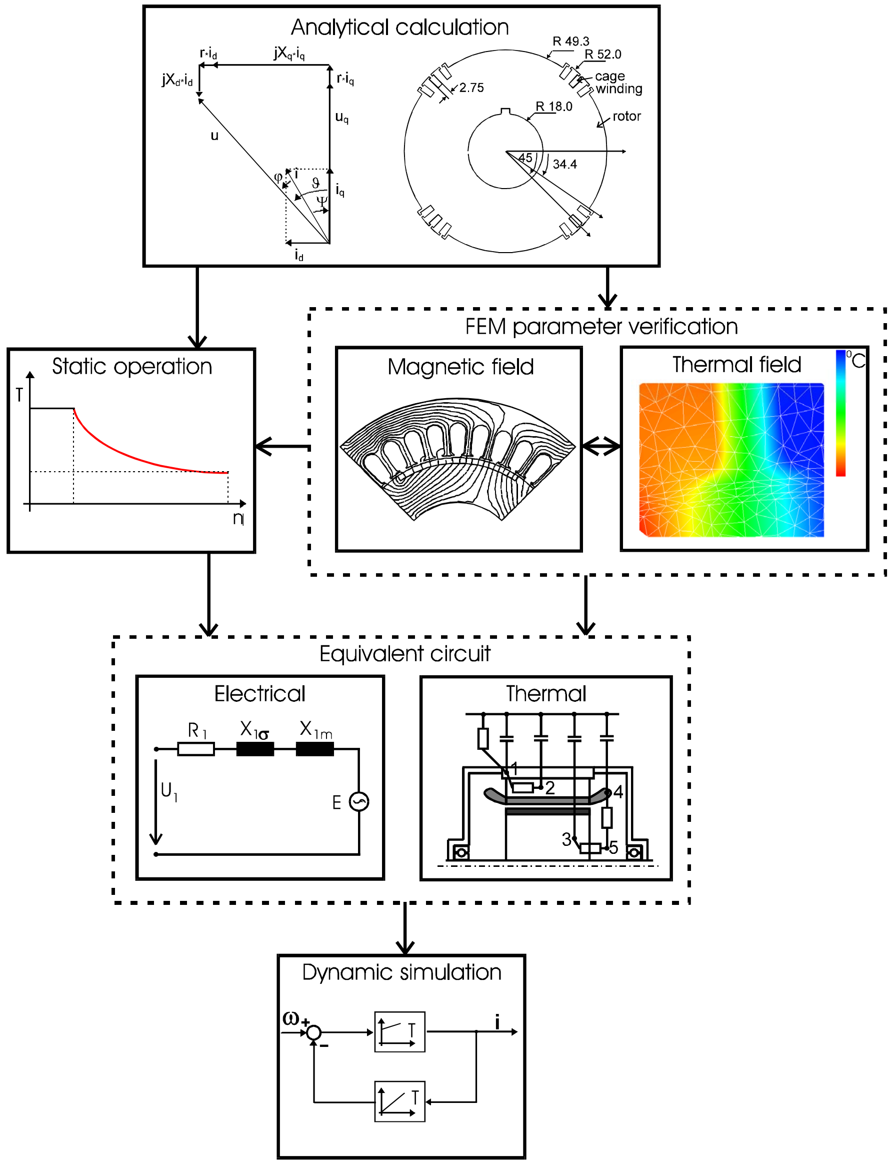

Figure 5: Principle of the design tool.

3. PRACTICAL APPLICATION OF THE DESIGN TOOL

Two different examples are used to demonstrate the flexibility of the design tool. The first one is a high performance motor drive for hybrid vehicles, requiring flux weakening at high speed. The second one aims at high efficiency, driving a pump supplied by a photovoltaic energy source.

3.1 Hybrid Vehicle

An electric vehicle motor design requires high efficiency, extended field weakening range, high power/weight ratio and high reliability. Water cooling, high energy density permanent magnets and special control strategies are applied in order to fulfil these requirements. One of the main design goals for the studied drive system is the continuous operation of the PMSM at high efficiency. Therefore, a rotor geometry with $X_q > X_d$ is chosen to benefit from an additional reluctance torque [13].

In order to achieve a high efficiency of the PMSM, the losses have to be kept low being contrary to a high power/weight ratio. Therefore, the optimal choice between low weight and acceptable iron losses has to be made. In the same way, the contributing losses can be reduced by using more winding copper, yielding increasing costs and additional weight. The thickness of the iron yoke is reduced by applying a high number of poles. However, the number of poles is limited by the frequency of the inverter and a wide range of field weakening can only be achieved by a relatively small number of poles. Iron losses are further decreased by choosing thin low-loss lamination in the stack of the stator. The power/weight ratio is further improved by applying an indirect water cooling system.

A high L_d value extends the field weakening range. However increasing L_d by decreasing the thickness of the permanent magnets has its limits. It enables the demagnetisation of the magnet poles and reduces the reluctance torque by decreasing the ratio L_q/L_d. The design procedure results in a motor design shown in Figure 6 with the dimensions summarised in Table 1, fulfilling the performances listed in Table 2.

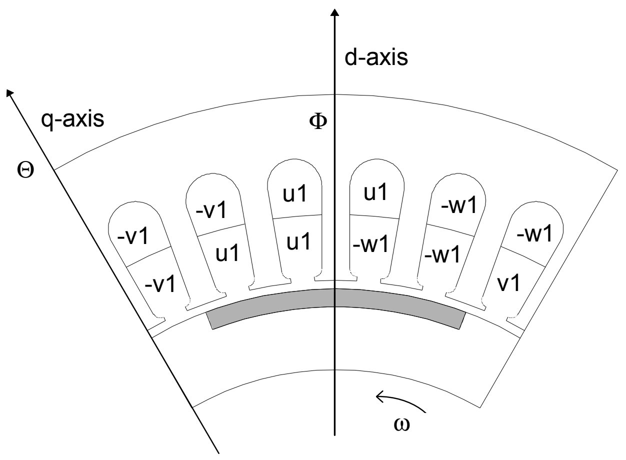

Figure. 6: Cross-sectional view of a 6-pole PMSM for an electric vehicle.

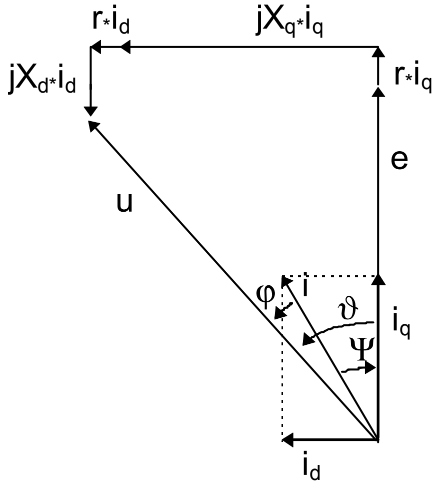

Figure 7: Phasor diagram of the PMSM in the advanced field weakening mode.

Table 1: Motor dimensions

stack outer diameter	287 mm
stack inner diameter	197 mm
rotor length	125 mm
overall mass	67.4 kg *
number of poles	6

* estimated for series production

Table 2: Motor performances

rated power	44.7 kW
rated torque	207 Nm
power/weight	0.75 W/kg
field-weakening range	$3.5*n_r$
efficiency	96,2 %

3.2 Photovoltaic Pump System

Photovoltaic systems have to reach a high efficiency during approximately seven hours a day, in which more than 80 % of the total daily solar energy is available. This corresponds to the requirements for a motor operating with low losses in a large power range, from 50 % to 100 % of its rated power. Therefore, a 3,5 kW PMSM is developed, to replace induction motors in submersible installations, which supply drinking water in small villages in the Sahel area. The slightly increased costs of the motor are not significant because the improved efficiency decreases the costs for the necessary photovoltaic cells.

The highest efficiency can be provided by reducing the losses assuming that in this application the weight of the motor is of minor importance. The losses in the stator iron can be decreased using a larger iron volume in the stator of the machine, as well as using more copper in order to reduce the ohmic losses. Iron losses are decreased by choosing thin low-loss iron laminations in the stack of the stator. Half closed slots are reducing the slot harmonics. Eddy current losses are decreased by using multiple surface mounted permanent magnet blocks, glued onto the rotor surface. The rotor wears an additional squirrel cage winding as damper circuit in order to have the motor operated in “open loop” mode avoiding an expensive position sensor. Therefore, the angular magnet width is restricted to give space to the rotor bars. To maximise the influence of the rotor bars, the air gap between the magnets has to be larger than the opening of the stator slots. Thus, the motor has a significant saliency and can be compared to a PMSM with surface-inset magnets [12] (Figure 8).

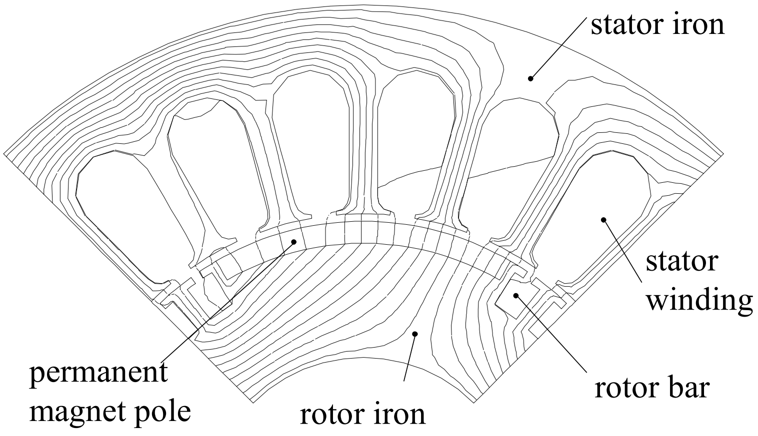

Figure 8: Flux lines of the PMSM at rated load.

4. CONCLUSIONS

The different requirements put upon permanent magnet motors raised the demand for a strategic design tool that operates flexible and accurate. Combining four design steps, an engineering tool is developed capable to handle these problems. Starting with analytical calculations followed by numerical field computations considering magnetic as well as thermal aspects. Finally the dynamic behaviour of the machine is simulated. The design tool takes its efficiency from the close and direct links of its components. Two different examples are discussed to demonstrate the flexibility of this approach.

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